

# Spatial clustering of USS sources and galaxies<sup>\*</sup>.

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## ABSTRACT

We present measurements of the clustering properties of galaxies in the field of redshift range  $0.5 \lesssim z \lesssim 1.5$  Ultra Steep Spectrum (USS) radio sources selected from Sydney University Molonglo Sky Survey and NRAO VLA Sky Survey. Galaxies in these USS fields were identified in deep near-IR observations, complete down to  $K_s = 20$ , using IRIS2 instrument at the AAT telescope. We used the redshift distribution of  $K_s < 20$  galaxies taken from Cimatti et al. (2002) to constrain the correlation length  $r_0$ . We find a strong correlation signal of galaxies with  $K_s < 20$  around our USS sample. A comoving correlation length  $r_0 = 14.0 \pm 2.8 h^{-1}$  Mpc and  $\gamma = 1.98 \pm 0.15$  are derived in a flat cosmological model Universe.

We compare our findings with those obtained in a cosmological N-body simulation populated with GALFORM semi-analytic galaxies. We find that clusters of galaxies with masses in the range  $M = 10^{13.4-14.2} h^{-1} M_\odot$  have a cluster-galaxy cross-correlation amplitude comparable to those found between USS hosts and galaxies. These results suggest that distant radio galaxies are excellent tracers of galaxy overdensities and pinpoint the progenitors of present day rich clusters of galaxies.

**Key words:** cosmology: large-scale structure of Universe—galaxies: galaxies: high-redshift.

## 1 INTRODUCTION

In hierarchical galaxy formation models, cosmic structures form by the gravitational amplification of small primordial fluctuations of matter density in the early Universe (White & Rees 1978). Studies of the clustering properties of galaxies at high redshift are essential for understanding galaxy and structure formation. One of the most commonly used statistics to measure the clustering of a population of sources is the two-point correlation function  $\xi(r)$ , which measures the excess probability of finding a pair of objects at a separation  $r$  with respect to a random distribution.

High redshift radio galaxies are ideal targets for pinpointing massive systems. Radio galaxies follow a close relation in the Hubble  $K - z$  diagram (Lilly & Longair 1984). The nature of this behavior in the  $K - z$  diagram

shows that the stellar luminosities of  $z \gtrsim 1$  radio galaxies are more luminous than normal galaxies at these redshifts (De Breuck et al. 2002). At lower redshifts they are found frequently in moderately rich clusters (Hill & Lilly 1991; Yates et al. 1989). Recently, galaxy overdensities comparable to that expected for clusters of Abell class 0 richness are found near radio galaxies up to  $z = 1.6$  (Best 2000; Best et al. 2003; Bornancini et al. 2004). There is increasing evidence that galaxy overdensities around radio galaxies existed at very high redshifts. Using Ly $\alpha$  and/or H $\alpha$  techniques, Kurk et al. (2000); Venemans et al. (2002); Miley et al. (2004) found overdensities of companion galaxies around powerful  $2 < z < 4$  radio galaxies.

In this paper we estimated the spatial correlation length for galaxies in the fields of USS targets selected from the 843 MHz Sydney University Molonglo sky Survey (SUMSS) and 1.4 GHz NRAO VLA Sky Survey (NVSS) in the redshift range  $0.5 \lesssim z \lesssim 1.5$ , through the Limber's equation using an appropriate observed redshift distribution. We compared our results with those obtained in cosmological N-body sim-

\* Based on observations obtained with the Australia Telescope Compact Array, the Anglo-Australian Telescope (Program 70.A-0514)

ulations. This paper is organized as follows: Section 2 describes the sample analyzed, we investigate the USS-galaxy cross-correlation analysis in Section 3. In Section 4 we interpret our results with those obtained in a cosmological N-body simulation. Finally we discuss our results in Section 5.

Throughout this paper we will use a flat cosmology with density parameters  $\Omega_M = 0.25$ ,  $\Omega_\Lambda = 0.75$  and a Hubble constant  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2 THE DATA

The USS sample selection, radio data and redshifts used for this analysis was presented and described by De Breuck et al. (2004, 2005). Detailed descriptions of the construction of the galaxy catalogue is given in Bornancini et al. (2005). In summary, we used 11  $K_s$ -band images centered in Ultra Steep Spectrum (USS) radio sources selected from the Sydney University Molonglo sky Survey and NRAO VLA Sky Survey, obtained with the instrument IRIS2 at the AAT telescope. We selected the redshift of the USS sample in the range  $0.5 \lesssim z \lesssim 1.5$ . The redshift upper limit was adopted in order to assure that  $K$ -band images are sufficiently deep while the lower limit precludes the use of too close USS for which the field of view subtends too small linear scales.

Our sample sources is listed in Table 1 in IAU J2000 format, including the  $K_s$  counterpart magnitude and the spectroscopic redshift (De Breuck et al. 2005).

## 3 USS-GALAXY CROSS-CORRELATION ANALYSIS

The spatial USS-galaxy cross-correlation function  $\xi_{ug}(r)$  is defined as the excess probability  $dP$  of finding a galaxy in the volume element  $dV$  at a distance  $r$  from a USS target,

$$dP = \bar{n} [1 + \xi_{ug}(r)] dV, \quad (1)$$

where  $\bar{n}$  is the mean space density of galaxies. The spatial two-point cross-correlation function  $\xi_{ug}(r)$  has been shown to be well approximated by a power law:

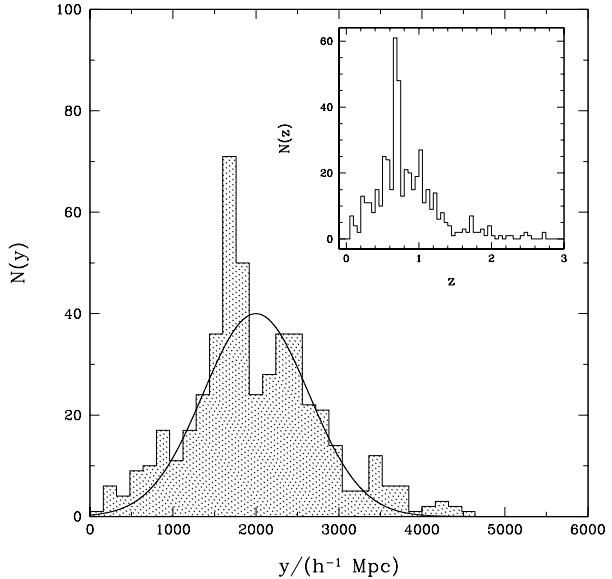
$$\xi_{ug}(r) = \left( \frac{r}{r_0} \right)^{-\gamma}. \quad (2)$$

In order to obtain the cross-correlation length  $r_0$  we first determine the projected cross-correlation function  $\omega_{ug}(\sigma)$ , where  $\sigma$  is the projected separation between a USS target and a galaxy at redshift  $z$ .

We use the following estimator of the projected cross-correlation function, (Peebles 1980):

$$\omega(\sigma) = \frac{n_R}{n_G} \frac{UG(\sigma)}{DR(\sigma)} - 1, \quad (3)$$

where  $n_G$  and  $n_R$  are the numbers of galaxies in the sample and in a random sample respectively,  $UG(\sigma)$  is the number of real USS-galaxy pairs separated by a projected distance in the range  $\sigma$ ,  $\sigma + \delta\sigma$ , and  $DR(\sigma)$  are the corresponding pairs when considering the random galaxy sample. We estimate the corresponding correlation length using the Limber equation (Limber 1953). The power law model for  $\xi_{ug}(r)$  gives:



**Figure 1.** Distance distribution for  $K_s < 20$  galaxies taken the K20 survey (Cimatti et al. 2002). The dashed curve shows the selection function obtained fitting a Gaussian function. The upper small box shows the corresponding redshift distribution of the sample.

$$\omega(\sigma) = B \sqrt{\pi} \frac{\Gamma[(\gamma - 1)/2]}{\Gamma(\gamma/2)} \frac{r_0^\gamma}{\sigma^{\gamma-1}}, \quad (4)$$

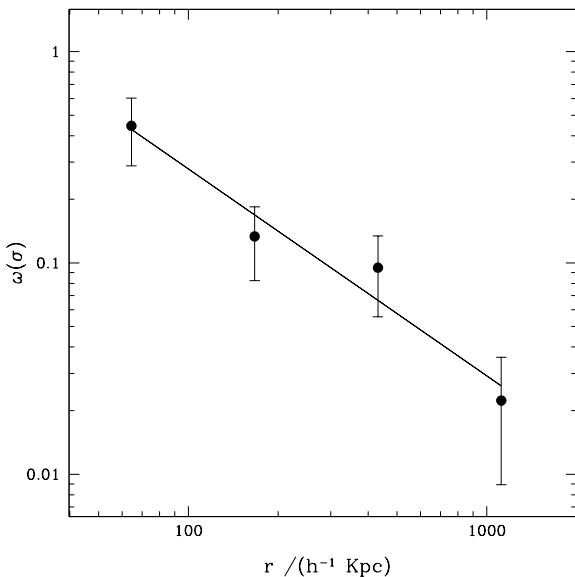
where the constant  $B$  regulates the amplitude of the correlation function taking into account the differences in the selection function of USS targets and galaxies and can be calculated by (Lilje & Efstathiou 1988):

$$B = \frac{\sum_i N(y_i)}{\sum_i \frac{1}{y_i^2} \int_0^\infty N(x) x^2 dx}, \quad (5)$$

where  $N(y_i)$  is the selection function of the galaxy survey,  $y_i$  is the distance to USS target  $i$  and the sum extends over all USS targets in the sample. Equation 4 can be easily solved analytically if we perform a linear interpolation of  $\omega_{ug}$  between its values at the measured  $\sigma$ 's. In order to calculate the constant  $B$  we evaluated the selection function  $N(y_i)$  using the redshift (spectroscopic and photometric) distribution of  $K_s < 20$  galaxies published by Cimatti et al. (2002)<sup>1</sup>. We model the distance distribution using a Gaussian function, and find that  $\bar{y} = 2000 h^{-1} \text{ Mpc}$  (mean) and  $\sigma_y = 635 h^{-1} \text{ Mpc}$  (standard deviation) is a reasonable set of values that reproduces the distribution (See Figure 1). In Figure 2 we show the projected cross-correlation function  $\omega_{ug}(\sigma)$  for USS targets with spectroscopic redshifts in the range  $0.6 \lesssim z \lesssim 1.5$  and galaxies with  $K_s < 20$ . We estimate cross-correlation function error bars using the *jackknife* technique (Efron 1982). We find a comoving correlation length  $r_0 = 14.0 \pm 2.8 h^{-1} \text{ Mpc}$  with slope  $\gamma = 1.98 \pm 0.04$ .

We tested the accuracy of this result by varying the  $N(y_i)$  distribution over a reasonable range of values for  $\bar{y}$  and

<sup>1</sup> Data and further information available at <http://www.arcetri.astro.it/~k20/releases>



**Figure 2.** Projected cross-correlation function  $\omega_{ug}(\sigma)$  for USS targets with spectroscopic redshift in the range  $0.6 \lesssim z \lesssim 1.5$ . The error bars correspond to the  $1\sigma$  uncertainty estimated using the jackknife technique.

$\sigma_y$ . We find that the calculated  $r_0$  is only weakly dependent on the  $\bar{y}$  used, and is only affected at the 10% level.

#### 4 COMPARISON WITH N–BODY SIMULATIONS

We interpret our results with the aid of a cosmological N–body simulation populated with GALFORM semi-analytic galaxies (Cole et al. 2000) at different outputs corresponding to different redshifts,  $z = 0, 1$ , and  $3$ . This simulation was kindly provided by the Durham group. The cosmological model corresponds to matter and cosmological constant density parameters  $\Omega_m = 0.25$ ,  $\Omega_\Lambda = 0.75$ , a power spectrum tilt  $n = 0.95$ , an amplitude of fluctuations of  $\sigma_8 = 0.8$ , and a Hubble constant of  $H_0 = 100 h \text{ kms}^{-1} \text{ Mpc}^{-1}$ , where  $h = 0.7$ . The total number of particles is  $1080^3$ , the mass resolution is  $5.05 \times 10^{10} h^{-1} M_\odot$ , and the number of dark matter haloes with masses greater than  $M = 10^{12} h^{-1} M_\odot$  ranges from  $\sim 400,000$  at  $z = 3$  to  $\sim 2,200,000$  at  $z = 0$ . The number of GALFORM galaxies ranges from  $\sim 20,000,000$  to  $120,000,000$  at  $z = 3$  and  $z = 0$  respectively.

We now briefly explain the procedure by which galaxies are assigned their properties in the Semi-analytic code. GALFORM is run for each halo in the numerical simulation, where galaxies are assigned to a randomly selected dark matter halo particle. The different galaxy properties such as magnitudes in different bands, including the  $K$ -band, depend on the dark matter halo merger tree. This merger tree is generated via Monte-Carlo modelling based on the extended Press-Schechter theory, and the evolution of the galaxy population in the halo is followed through time and different processes are considered in this evolution, including gas cooling, quiescent star formation and star formation bursts, mergers, galactic winds and super winds, metal

enrichment, extinction by dust. For full details on the modelling the reader is referred to Cole et al. (2000).

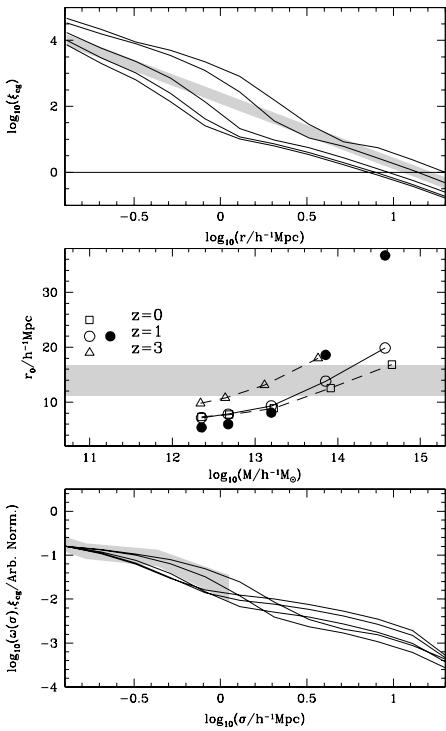
We calculate the cross-correlation function using the simulation haloes with masses above a lower mass limit as centres, and as tracers, the GALFORM semi-analytic galaxies. By comparing these measurements to the results from the cross-correlation between USS and normal galaxies, we make the implicit assumption that USS galaxies reside at the centres of dark-matter haloes. This comparison will make it possible to infer the mass of the structures associated to the USS hosts.

Figure 3 shows the resulting real-space cross-correlation functions between haloes and semi-analytic galaxies at  $z = 1$  (top panel) for different halo masses. The shaded area corresponds to the power law fit for the real-space correlation function inferred from the cross-correlation function for USS radio sources with spectroscopic redshifts in the range  $0.6 \lesssim z \lesssim 1.5$  (See Figure 2). In the middle panel of this figure, we compare the values of USS–galaxy cross-correlation length as a function of halo mass for three different redshift outputs from the numerical simulations; as can be seen, the observed values are consistent with cluster masses within  $M = 10^{13.4-14.2} h^{-1} M_\odot$  at redshift  $z=1$ , indicating that our USS sample resides in massive clusters. In order to check whether our observational estimate of  $r_0$  is affected by systematic biases, we calculate the projected correlation function in the numerical simulation and recover the real-space correlation length using Eq. 4, setting  $B = 1$ ; we consider the same range of separations available in the real data. The results for  $z = 1$  are shown in filled circles in the middle panel. As can be seen, our conclusions on the mass of USS host haloes changes only slightly to  $M = 10^{13.2-13.8} h^{-1} M_\odot$ , although we note that for lower and higher halo masses, the value of  $r_0$  recovered from projected correlations is underestimated and overestimated, respectively. This test provides a useful check of our observational results which were derived from relatively small projected scales ( $r_p \lesssim 1 \text{ Mpc}$ ). Our findings in the simulations indicate that reliable  $r_0$  values are obtained using the power law approximation applied to projected correlations for  $r_p < 1 h^{-1} \text{ Mpc}$  when the true correlation length is lesser than  $\sim 15 h^{-1} \text{ Mpc}$  corresponding to host halo mass  $M \lesssim 10^{14} M_\odot$ .

A further indication of the mass of USS galaxy host haloes comes from the lower panel of this figure, where the lines correspond to the projected cross-correlation function measured in the GALFORM simulation for different masses (High to low masses from top to bottom lines at  $\log_{10}(\sigma/h^{-1} \text{ Mpc}) = -0.3$ ).  $\Xi(\sigma)$  is calculated directly using,

$$\Xi(\sigma) = \text{Norm. } 2 \int_0^{\pi_{max}} \xi(\sqrt{\sigma^2 + \pi^2}) d\pi, \quad (6)$$

where we have used  $\pi_{max} = 80 h^{-1} \text{ Mpc}$ , and the normalisation, Norm., is set so that  $\Xi(\sigma)$  and  $\omega(\sigma)$  coincide at  $\log_{10}(\sigma/h^{-1} \text{ Mpc}) = -1$ . The gray area shows the measured values of  $\omega(\sigma)$  from the USS sample; as can be seen the measured projected correlation function is in best agreement for  $M \sim 10^{13.85} h^{-1} M_\odot$ .



**Figure 3.** Top panel: cluster-galaxy cross-correlation functions from the simulation output at  $z = 1$  for increasing halo masses  $\text{Log}(M) = 12.35, 12.68, 13.2, 13.85$  and  $14.57 h^{-1} M_{\odot}$  (bottom to top). The shaded area shows the real-space correlation function measured from the USS targets with spectroscopic redshift in the range  $0.6 \lesssim z \lesssim 1.5$ . Middle panel: the real-space correlation length,  $r_0$ , as a function of halo mass for three different redshift outputs; the open symbols show the values recovered from the real-space correlation function, whereas the filled symbols (shown only for  $z = 1$ ) indicate the values of  $r_0$  obtained from the projected correlation function following a similar procedure to that applied to the real data. The shaded area shows the allowed range of  $r_0$  for the USS results. Bottom panel: the projected USS cross-correlation function (gray area) and  $\Xi(\sigma)$  from the GALFORM simulation for the same halo masses as in the top panel; the normalisation is set so that  $\Xi(\sigma)$  and  $\omega(\sigma)$  coincide at  $\log_{10}(\sigma/h^{-1}\text{Mpc}) = -1$ .

## 5 CONCLUSIONS

We have analyzed the clustering properties of galaxies in the field of  $0.5 \lesssim z \lesssim 1.5$  Ultra Steep Spectrum (USS) radio galaxies selected from the Sydney University Molonglo Sky Survey (SUMSS) and NRAO VLA Sky Survey (NVSS). We estimated the spatial clustering correlation length for galaxies in these fields, using the Limber equation using an appropriate observed redshift distribution, and we examined the dependence of galaxy clustering on USS targets luminosity. A comoving correlation length  $r_0 = 14.0 \pm 2.8 h^{-1} \text{Mpc}$  is derived and a slope  $\gamma = 1.98 \pm 0.15$ .

From our comparison with numerical simulations, we find that clusters of galaxies with masses in the range  $M = 10^{13.4-14.2} h^{-1} M_{\odot}$  have a cluster-galaxy correlation amplitude comparable to that found between USS hosts and

galaxies. Our testing with the numerical simulations also indicate that these observational results are not severely affected by the relatively small projected scales explored. We notice that for larger spatial correlation lengths, the power-law extrapolation for observed projected correlations in  $\sim 1 h^{-1} \text{Mpc}$  fields would not give confident results.

Previous studies have addressed the clustering of galaxies around radio sources. Wold et al. (2000), using different cosmological parameters obtained a radio quasar-galaxy cross-correlation length about twice as large as the local galaxy autocorrelation length in suitable agreement with our findings. The more recent work by Barr et al. (2003) also indicates a moderate galaxy density enhancement around radio loud quasars similar to Abell richness 0 clusters.

Our analysis suggest that distant luminous radio galaxies are excellent tracers of galaxy overdensities and may pinpoint the progenitors of present day rich and moderate rich clusters of galaxies.

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Table 1. USS Sample characteristics. Designation in IAU J2000 format, together with the  $K_s$  counterpart magnitude, and the spectroscopic redshift (De Breuck et al, in prep.).

(1) Name	(2) K-mag. MAG_BEST	(3) $z$ spectroscopic
NVSS J015232–333952	16.26±0.02	0.6148±0.001
NVSS J015544–330633	16.93±0.05	1.048±0.002
NVSS J021716–325121	18.75±0.20	1.384±0.002
NVSS J030639–330432	17.88±0.11	1.201±0.001
NVSS J202026–372823	18.56±0.15	1.431±0.001
NVSS J204147–331731	16.86±0.05	0.871±0.001
NVSS J225719–343954	16.53±0.02	0.726±0.001
NVSS J230203–340932	17.34±0.07	1.159±0.001
NVSS J231519–342710	18.10±0.13	0.970±0.001
NVSS J234145–350624	15.94±0.04	0.641±0.001
NVSS J234904–362451	17.63±0.14	1.520±0.003

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